

Does quark number scaling breakdown in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV?

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The anisotropy coefficient v_2 , for unidentified and identified charged hadrons [pions (π), kaons (K) and protons (p)] measured in Au+Au collisions at $\sqrt{s_{NN}} = 0.20$ TeV (RHIC) and Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV (LHC), are compared for several collision centralities (cent) and particle transverse momenta p_T . In contrast to the measurements for charged hadrons, the comparisons indicate a sizable increase of $v_2(p_T)$ for π , K and p , as well as a blueshift of proton $v_2(p_T)$, from RHIC to LHC. When this blueshift is accounted for, the LHC data [for π , K , p] show excellent scaling of $v_2(KE_T)$ with the number of valence quarks (n_q), for a broad range of transverse kinetic energies (KE_T) and collision centralities. These observations suggest a larger mean sound speed $\langle c_s(T) \rangle$ for the plasma created in LHC collisions, and significant radial flow generation after its hadronization.

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Anisotropic flow measurements for identified and unidentified charged hadrons are currently being pursued at both the Relativistic Heavy Ion Collider and the Large Hadron Collider, to aid investigations of the temperature (T) dependence of the equation of state (EOS) and other transport properties of the hot and dense plasma produced in energetic heavy ion collisions [1–10]. An important lever arm for these efforts is the measured energy density increase of more than a factor of three from RHIC to LHC [11]. This increase could result in a change in the mean specific shear viscosity $\langle \frac{\eta}{s}(T) \rangle$ (the ratio of shear viscosity η to entropy density (s)), as well as a change in the value of the mean sound speed $\langle c_s(T) \rangle$. Either could have a significant influence on the expansion dynamics, which in turn, influences the magnitude and trend of anisotropic flow. Thus, a crucial question is the extent to which flow measurements for identified and unidentified charged hadrons differ from RHIC to LHC, and whether any characterizable difference reflects the sizable increase in energy density from RHIC to LHC?

Flow manifests as an anisotropic emission of particles in the plane transverse to the beam direction [12, 13], and is often characterized via Fourier decomposition of the measured azimuthal distribution for these particles;

$$\frac{dN}{d(\phi - \Psi_n)} \propto \left(1 + \sum_{n=1} 2 v_n \cos(n[\phi - \Psi_n]) \right), \quad (1)$$

where ϕ is the azimuthal angle of an emitted particle, $v_n = \langle \cos(n[\phi - \Psi_n]) \rangle$, $n = 1, 2, 3, \dots$ and the Ψ_n are the generalized participant event planes at all orders for each event. Characterization can also be made via the pairwise distribution in the azimuthal angle difference ($\Delta\phi = \phi_1 - \phi_2$) between particle pairs with transverse momenta p_T^a and p_T^b (respectively) [8, 13, 14];

$$\frac{dN_{\text{pairs}}}{d\Delta\phi} \propto \left(1 + \sum_{n=1} 2 v_n^a(p_T^a) v_n^b(p_T^b) \cos(n\Delta\phi) \right). \quad (2)$$

A sizable pseudorapidity-gap ($\Delta\eta'$), which serves to minimize possible non-flow effects, is usually imposed between the particles in each pair to ensure consistency between the v_n coefficients obtained via Eqs. 1 and 2 [8, 15].

Current RHIC v_n measurements can be understood in terms of an eccentricity-driven hydrodynamic expansion of the high energy density quark gluon plasma (QGP) created in the overlap zone of the two colliding Au nuclei [16–30]. That is, a finite eccentricity ε_n , drives uneven pressure gradients in- and out of the Ψ_n event plane, and the resulting expansion of the plasma, modulated by a relatively small $\langle \frac{\eta}{s}(T) \rangle$ value, leads to anisotropic particle emission about this plane. The observation that $v_n(KE_T)/(n_q)^{n/2}$ vs. $KE_T/(n_q)$ gives a universal curve for a broad spectrum of particle species [termed Quark Number Scaling (QNS)] [3, 31, 32], also gives a strong indication that anisotropic flow at RHIC develops primarily in the partonic phase, and is not strongly influenced by the subsequent hadronic phase.

The LHC v_n measurements can also be understood in terms of an eccentricity-driven hydrodynamic expansion of the QGP created at a much higher energy density, in Pb+Pb collisions. However, recent comparisons of RHIC and LHC $v_2(p_T)$ data for unidentified charged hadrons, have indicated a striking similarity between the two sets of measurements [1, 33]. This similarity posed an initial conundrum because the significant increase in energy density for LHC collisions, is expected to influence the expansion dynamics and hence, the magnitude of $v_2(p_T)$. Initial estimates of $\langle \frac{\eta}{s}(T) \rangle$ from LHC charged hadron data, have not indicated a sizable change from RHIC to LHC [33–35]. However, in contrast to RHIC results, tests for QNS with LHC data for identified charged hadrons, have indicated an apparent breakdown of this scaling [2].

In this work we present comparisons of RHIC and LHC flow measurements for both unidentified and identified charged hadrons, to further investigate whether the siz-

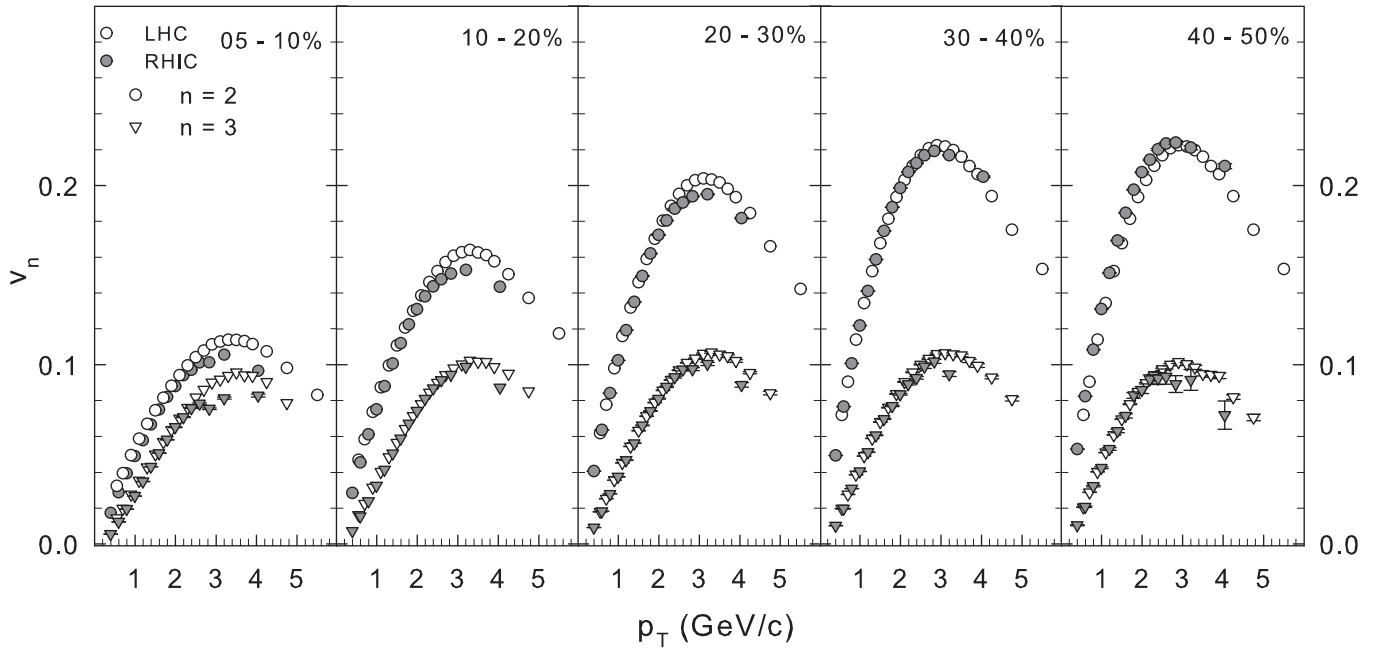


FIG. 1. Comparison of $v_{2,3}(p_T)$ for charged hadrons obtained in Au+Au collisions at $\sqrt{s_{NN}} = 0.20$ TeV (RHIC) and Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV (LHC). The data are taken from Refs. [5, 7] and [8].

able increase in energy density from RHIC to LHC, signals a possible change in the expansion dynamics. We also study how such a change could manifest as a breakdown of quark number scaling.

The double differential measurements $v_2(p_T, \text{cent})$ employed in our comparisons are taken from the unidentified charged hadron results reported by the PHENIX [5, 7] and ATLAS [8] collaborations, as well as the measurements reported for identified charged hadrons by the PHENIX [6] and ALICE collaborations [2].

To initiate our comparisons, we show RHIC and LHC $v_{2,3}(p_T)$ measurements for unidentified charged hadrons (h) for several centrality selections in Fig. 1. A comparison of the $v_2(p_T)$ measurements indicates good agreement between the magnitude and trends of both data sets for a broad range of p_T and centralities, as previously reported [1, 33]. The comparison also indicates that the observed similarity between RHIC and LHC charged hadron measurements extends to the higher harmonics.

The $v_2(p_T)$ results for charged hadrons are actually a weighted average of the values for identified charged hadrons. Consequently, one can test for consistency between the measured values of $v_2(p_T)$ for identified and unidentified charged hadrons. Such a consistency check is shown for LHC data in Fig. 2. The left panel of Fig. 2 shows that, while $v_2(p_T)$ for K and h are similar for most of the p_T range, they are significantly different from the values for π and p . The right panel of Fig. 2 shows that an appropriate averaging of the same $v_2(p_T)$ values for π , K and p (with weights derived from the measured p/π and K/π ratios), gives average values which are es-

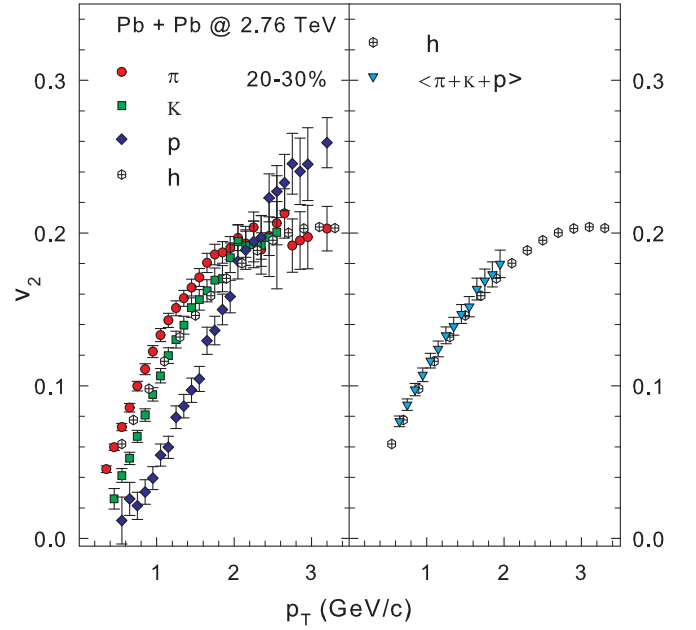


FIG. 2. (color on line) (a) Comparison of $v_2(p_T)$ vs. p_T for π , K , p and unidentified charged hadrons h . (b) Comparison of $v_2(p_T)$ for h and the weighted average of the values for π , K and p . The data for identified and unidentified charged hadrons, are from the ALICE [2] and ATLAS [8] collaboration respectively. Results are shown for the 20-30% most central Pb+Pb collisions.

106 sentially the same as those for h .

107 Given the substantial differences between the LHC

$v_2(p_T)$ values for π, K and p shown in the left panel of Fig. 2, it is important to ask whether the agreement observed between RHIC and LHC data for h (Fig. 1) translates to a similar agreement between RHIC and LHC measurements for π, K and p (respectively)? Fig. 3 compares the RHIC (open circles) and LHC (filled red circles) $v_2(p_T)$ values for π, K and p for the 20-30% most central events. The values for π and K give a clear indication that the LHC values are approximately 20% larger than the RHIC values. This is confirmed by the excellent agreement between RHIC and LHC measurements after the scale factor ~ 1.2 is applied to the RHIC data (filled circles in left and middle panels of Fig. 3).

For $p_T \gtrsim 2.5$ GeV/c, the results for protons, shown in the right panel of Fig. 3, also hint at a 20% difference between the RHIC and LHC values. For lower p_T ($p_T \lesssim 2.0$ GeV/c) however, the RHIC $v_2(p_T)$ values appear to be larger than the LHC values. We attribute this inversion to a small blueshift of the LHC values. Such a blueshift has been observed in recent viscous hydrodynamical calculations for LHC collisions [36], and can be linked to a sizable increase in the magnitude of the radial flow generated in these collisions, especially in the hadronic phase. Here, the blueshift is confirmed by the excellent agreement obtained between the proton measurements, when the RHIC data are scaled by the factor ~ 1.2 (as for π and K) and then blueshifted by ~ 0.2 GeV/c (filled squares in right panel of Fig. 3). Similarly good agreement between RHIC and LHC measurements were obtained for other centrality selections, with essentially the same blueshift value. However, a larger (smaller) scale factor was required for more central (peripheral) collisions, as might be expected from the change in energy density with collision centrality.

The results from the comparisons shown in Fig. 3, suggest that the agreement observed between the charged hadron measurements in Fig. 1, may be inadvertent. Thus, the comparisons for charged hadrons might not convey all of the essential information about the expansion dynamics. By contrast, the observed increase in $v_2(p_T)$ from RHIC to LHC for identified charged hadrons (Fig. 3), suggests that the expansion dynamics in LHC collisions is driven by a larger mean sound speed $\langle c_s(T) \rangle$ for the plasma created in these collisions. Such an increase in $\langle c_s(T) \rangle$ could result from the sizable increase in energy density from RHIC to LHC.

The blueshift inferred for proton $v_2(p_T)$ in LHC collisions is incompatible with quark number scaling. Thus, it provides a straightforward explanation for the observed failure of this scaling, when applied to LHC data for identified charged hadrons (π, K and p) [2]. An appropriate correction for this blueshift would of course, lead to a restoration of quark number scaling. This is demonstrated for LHC data in Fig. 4, for a broad range of centrality selections. For these plots, the $v_2(p_T)$ data for protons were redshifted by ~ 0.2 GeV/c for each cen-

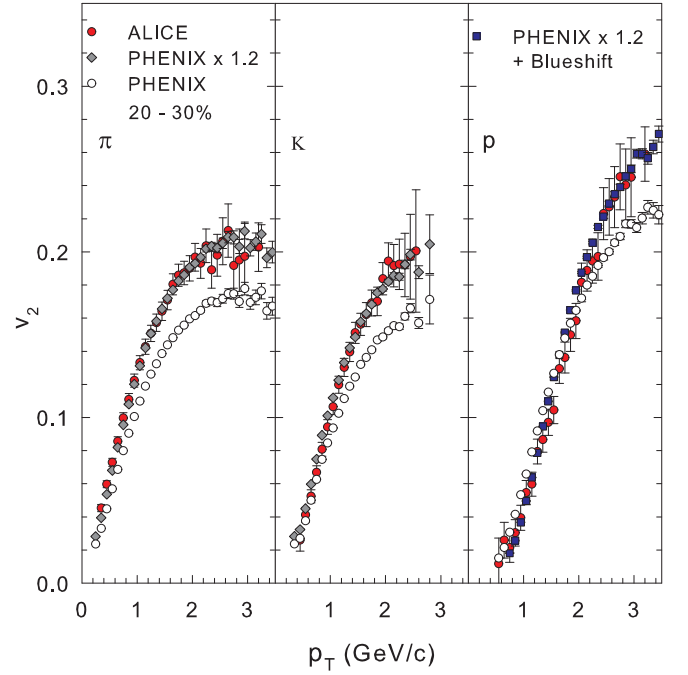


FIG. 3. (color on line) Comparison of PHENIX and ALICE data for $v_2(p_T)$ vs. p_T for π, K and p as indicated. Results are shown for the 20-30% most central collisions.

trality selection [prior to QNS scaling] to account for the blueshift (cf. right panel of Fig. 3) with the same magnitude. Fig. 4 shows that this procedure leads to excellent quark number scaling of the LHC data for identified charged hadrons, and confirms that partonic flow still dominates for LHC collisions. Note as well, that the magnitudes of the quark number scaled values of $v_2(KE_T)/n_q$ are significantly larger than those observed at RHIC.

In summary, we have performed detailed comparisons of RHIC and LHC flow data for unidentified and identified charged hadrons. In contrast to the agreement observed between the RHIC and LHC data sets for unidentified charged hadrons, $v_2(p_T)$ for π, K and p indicate a sizable increase from RHIC to LHC. This increase is compatible with the larger mean sound speed $\langle c_s(T) \rangle$, expected for the plasma created at a much higher energy density in LHC collisions. The comparisons also indicate a blueshift of LHC proton $v_2(p_T)$ relative to RHIC proton $v_2(p_T)$, possibly because of a sizable growth of radial flow in the hadronic phase for LHC collisions. When this blueshift is accounted for, excellent scaling of $v_2(KE_T)$ with the number of valence quarks is observed [for π, K, p] for a broad range of transverse kinetic energies and collision centralities. These results highlight the indispensable role of the measurements for identified particle species at both RHIC and the LHC, for studies of the temperature (T) dependence of the equation of state (EOS) and other transport properties.

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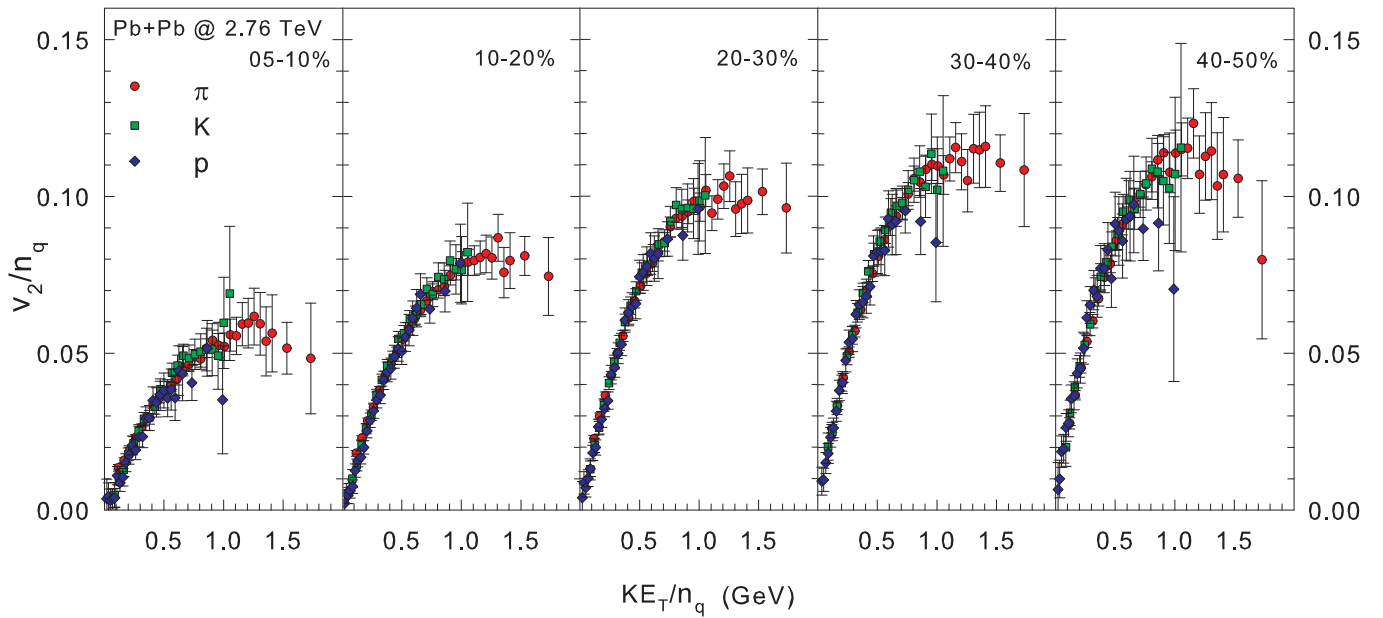


FIG. 4. (Color on line) $v_2(KE_T)/n_q$ vs. KE_T/n_q for pions, kaons and protons, after correcting for the proton blueshift (see text). Results are show for several centrality selections as indicated.

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